Modeling and Analysis of Modular Lunar Outpost Microgrid Architectures

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***Abstract* – The National Aeronautic and Space Administration (NASA) Space Technology Mission Directorate recently release a solicitation for Lunar Vertical Solar Array (VSAT) technology, which seeks proposals for the design and prototype fabrication of autonomously deployable and relocatable lunar surface solar arrays for future missions during the "Sustainment Period" of lunar South Pole exploration. The work presented here focuses on analyzing the architecture and system metrics of a lunar microgrid power by such Lunar VSAT devices. The main portions of this work are as follows: (i) modeling a Lunar VSAT system for power generation, (ii) modeling a lunar habitat for power load, (iii) modeling power storage, (iv) modeling power regulation, and (v) analyzing how modularity of the microgrid will affect the capabilities of a lunar microgrid. Results indicate that architectures that use a parallel ideology are better than architectures that use a single-string ideology, similar to the difference between the power transmission system and the power distribution system, respectively.**

***Index Terms* – lunar, base, solar, microgrid, power**

I. INTRODUCTION

According to the NASA Space Technology Mission Directorate (STMD) solicitation appendix [6], the goal of the solicitation is to enable the maturation of critical technologies across the mid-Technology Readiness Levels (TRL), namely TRL 3 through 6, via the Game Changing Development (GCD) program [7]. The solicitation focuses on enabling the development of solar arrays and related technologies necessary for sustained presence on the lunar surface, specifically with regards to the design and prototype fabrication of autonomously deployable and relocatable lunar surface solar arrays for future missions during the "Sustainment Period" of lunar South Pole exploration.

The Lunar VSAT solicitation explores vertical array deployment on masts of up to 10 meters in length to minimize shadowing in order to capture near-continuous sunlight at the lunar South Pole [6]. This is in contrast to existing solar array structures, which are designed for either zero-gravity or horizontal surface deployment [6].

While the solicitation itself focuses on the development of Lunar VSAT hardware for lunar exploration, this work focuses on the analysis of a lunar base microgrid. Previous research [4], [5] focuses on power generation via nuclear or related processes, but do not elaborate on the analysis of the microgrid itself. This work focuses on comparing various lunar base microgrid architectures with respect to system metrics such as losses and contingency analysis.

The paper is divided into the following sections: background, proposed method, simulation tool, numerical results, and conclusions, followed by references at the end. The background section covers research related to power generation for a lunar base. The proposed methods section details assumptions and mathematical formulations used to enable analysis of lunar microgrid architectures. The simulation tool section describes how the results in the numerical results section were obtained.

II. BACKGROUND

Development of a lunar base has been researched by the scientific community at least as far back as 1954, when two papers were published in the Journal of the British Interplanetary Society [3].

Much research on lunar base power generation focuses on the determining power requirements as well as producing power via popular forms of energy generation such as solar or nuclear. Colozza et al. [1] estimate that a lunar base consisting of (i) an in situ resource utilization (ISRU) system for producing oxygen and (ii) a lunar habitation module would need approximately 26 kW and 28 kW of power, respectively. This research goes on to detail how these power requirements can be met by the primary power generation system being nuclear with solar being a supplemental power generation system, with the primary drive of using nuclear being the long night cycle of 354 hours with a lunar base at 30° N latitude.

Landis et al. [2] note that the primary options for lunar base power systems are solar and nuclear. This research covers similar ground to the work done by Colozza et al., namely in providing details on lunar ISRU and habitation modules, going further to indicate that the power requirements for a lunar base during the night cycle would be approximately half of the normal day cycle power requirements. Landis et al. also acknowledge that the 354 hour night cycle is a large obstacle for an all-solar powered lunar base, and provide possible storage solutions including batteries, regenerative fuel cells (RFCs), and flywheels. This research also discusses alternative to power storage, namely by keeping the solar panels continuously illuminated during the night cycle by either (i) beaming power from Earth in the form of lasers and (ii) having the lunar base be entirely mobile so as to travel across the lunar surface and remain in the illuminated portion of the Moon.

Hu et al. [4] focus on nuclear power generation for a lunar base needing 10s of kW (for initial human visits) to 100s of kW (for a permanent lunar base). This research focuses exclusively on power generation and does not into detail on power requirements or power grid architecture. Mason et al. [5] also focus on nuclear power generation, but go into significant detail (similar to that of the work done by Colozza et al.) with respect to the power requirements of a lunar base.

III. PROPOSED METHOD

To begin this work, research was done to determine power system requirements for a lunar base. While many research papers focus on power generation specifically, a few detail the expected power load of a lunar base under various conditions. Another consideration is that while the power storage requirement portion of this research can be done via a simple power budget, the portion that allows for comparison of various lunar microgrid architectures requires simulation in order to achieve results. System losses were not analyzed in this research, as these were assumed to be negligible concerns when compared to the importance given to safety on human spaceflight missions. Because of this prioritization of safety, the focus of lunar microgrid architecture was given to contingency analysis. Losses could be taken into account in the future, as discussed in the Conclusions section of this paper.

A. Modeling

The NASA Lunar VSAT solicitation appendix also gives details as to power generation requirements for a lunar VSAT module. The values from these resources are detailed below, and act as the baseline assumptions for the research presented in this work. The result is that a single lunar VSAT module is modeled as a bus with (i) a solar generation component, (ii) a load component, and (iii) a storage component. The lunar base module is modeled as a bus with (i) a load component and (ii) a storage component. These bus models can be seen in Figure 1.

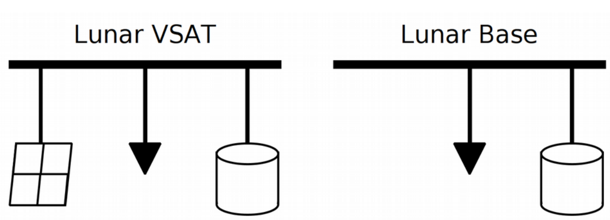

Fig. 1. Visualization of representations of a lunar VSAT module (left) and the lunar base module (right).

Human spaceflight missions prioritize safety, so analysis of how the different lunar microgrid architectures react to contingencies is vital in determining the best architecture to use for a lunar outpost. The contingencies that are considered here include the following: (i) failure of a single lunar VSAT module solar array, (ii) failure of a single lunar VSAT module battery, (iii) failure of a transmission line, and (iv) failure of a lunar base module battery. The worst-case scenario for these contingencies are those focused around the 4-day lunar night or the period just before it. For simplicity, the contingency was expected to last the full period in which it occurred. The effect of the contingencies on a given lunar microgrid architecture were analyzed by forcing the simulation to follow the dispatch schedule as if there would be no contingency up to the period before the contingency would occur, specifically by setting the lower bound and upper bound thresholds (discussed later) to be within a 0.1% margin of the original schedule (due to numerical accuracy limitations). The limits for the periods after the one in which the contingency occurs are not changed. This prevents the simulation from accounting for the contingency due to having foresight of the incident.

B. Mathematical Derivation/Formation

To determine power storage requirements, a simple power budget can be done. To do this, the following values need to be determined: (i) the power requirement or demand for a given system (P_D), (ii) the amount of time (T) that a power storage solution has to provide this power, (iii) the round-trip efficiency of the power storage solution (η), and (iv) the desired margin (μ). With this information, the power storage requirement (E_S) can be determined as follows:

$$E_S = P_D\, T\, (1 + \mu) / \eta \qquad (1)$$

This research also examines the power storage requirements of a lunar VSAT and lunar base system, which considers the scheduling of certain power generation when compared with energy storage, power charging, and power discharging. To do this, a given power storage solution has the following variables and limits: (i) the power charging (P_{SC}), (ii) the power discharging (P_{SD}), (iii) the energy stored (E_S), (iv) limits on these values $P_{SC\text{-}MAX}$, $P_{SC\text{-}MIN}$, $P_{SD\text{-}MAX}$, $P_{SD\text{-}MIN}$, $E_{S\text{-}MAX}$, $E_{S\text{-}MIN}$), and (v) the scheduling period in hours (γ). For the entire system, the power balance equation (2) must be satisfied for any point in time (where P_G is the total power generation), as well as the energy balance equation (3) for any point in time (where η_{SC} is the charging efficiency and η_{SD} is the discharging efficiency).

$$P_G(t) - P_D(t) + P_{SD}(t) - P_{SC}(t) = 0 \qquad (2)$$

$$E_S(t) = E_S(t\text{-}1) + \gamma\, \eta_{SC}\, P_{SC}(t) + \gamma\, \eta_{SD}\, P_{SD}(t) \qquad (3)$$

The power storage equations can be solved using linear programming, which seeks to minimize (4) subject to (5), (6), and (7), where c is cost function, x is the state variables, A and b form a system of inequalities, A_{eq} and b_{eq} form a system of equations, lb is the lower bounds for the state variables, and ub is the upper bounds for the state variables .

$$c^T x \tag{4}$$

$$A\,x \leq b \tag{5}$$

$$A_{eq}\,x \leq b_{eq} \tag{6}$$

$$lb \leq x \leq ub \tag{7}$$

C. Solution Method

The NASA Lunar VSAT solicitation appendix details a few key requirements of the solar power generation system, specifically: (i) each lunar VSAT solar array module should provide 10 kW of power when fully illuminated, (ii) the lunar VSAT module should be sun-tracking, and (iii) the transfer of power from the solar array to eventual end users will be via cables at a voltage of 1 kV [6]. Another key element from the NASA Lunar VSAT solicitation appendix is that the solar array must be able to transmit telemetry at a regular 4-hour interval, including during the 4-day lunar night cycle [6], and thus requires local power storage. This information is also used in this research to assume that the lunar base module must also maintain power for up to 4 days without the power generation of the lunar VSAT solar arrays. This research also assumes that the power storage on the lunar VSAT solar array module will not be used to provide power to the lunar base module, and that during the 4-day lunar night cycle, the power storage on the lunar base module will not be used to provide power to the solar array module.

While it was difficult to obtain information on the expected power needed to operate a lunar VSAT solar array module that is required to perform both solar tracking and provide telemetry at 4-hour intervals, Colozza et al. [1] provide estimates of 0.1 kW to 1.0 kW of power needed for systems such as a remote, stand-alone geology station and a remote, stand-alone astronomy observatory. Assuming that a lunar VSAT solar array module similarly has low power requirements, this research will assume that a lunar VSAT solar array module will need approximately 0.1 kW of power, or 1% of the expected 10 kW of power generation. This power requirement is also assumed to be constant through both the lunar day cycle and the lunar night cycle. This information is presented in Table 1.

Colozza et al. [1] gives very detailed information on the power requirements of a lunar base, down to specific sub-modules. The primary results of this are that for a lunar base supporting 6 crew members (i) the primary lunar habitat module was estimated to need a constant 28.05 kW of power, (ii) the ISRU system was estimated to need a constant 25.38 kW of power, and (iii) various smaller modules would need a total of 22.5 kW to 168 kW (with the primary load here being water ice exploration and recovery heat and power need 10 to 100 kW). Landis et al. [2] give information about the power requirements for different sizes of lunar bases, namely (i) an initial lunar base supporting 3 crew members needing 25 kW of power, (ii) a permanent lunar base supporting 10 crew members needing 100 kW of power, and (iii) the power required for a lunar base during the lunar night cycle could be cut to 50% of that needed during the lunar day cycle. Using this information, this research assumes that a single lunar base module will consume approximately 75 kW of power considering habitation, ISRU, and miscellaneous support equipment during a lunar day cycle and approximately 25 kW of power considering 50 kW for only habitation and ISRU and a 50% reduction in load during a lunar night cycle. This information is presented in Table 1.

TABLE 1
Power Requirements for Individual Modules

Module	Load (kW)
Lunar VSAT	0.1
Lunar Base (Day)	75
Lunar Base (Night)	25

Given that the load of a lunar base module during the lunar day cycle is 75 kW and the power provided by a single lunar VSAT module is only 10 kW, multiple lunar VSAT modules will need to be used in order to provide power to a single lunar base module. It is safe to assume that, considering the importance given to safety on human spaceflight missions, the number of lunar VSAT modules would be needed to cover the power requirements of a single lunar base module even after a failure of 1 of the lunar VSAT modules. Thus, the minimum number of lunar VSAT modules needed would be 9 modules for a total power generation capability of 90 kW (or 80 kW after failure of 1 module).

IV. SIMULATION TOOL

The MATLAB programming language was used to solve the linear programming setup for the energy storage scheduling simulation, specifically using the “linprog” function. For each case, the schedule granularity was broken into 4-day segments where the dispatch was considered to be constant during each 4-day period. The lunar VSAT solar arrays were modeled as standard DC power generators (assuming the module itself would be able to curtail power), and power storage discharge was given an arbitrary cost in order to prioritize using power generated by the solar arrays. The charging and discharging efficiencies for the power storage were also assumed to be equivalent, and were approximated by taking the square-root of the round-trip efficiency. Each group of 9 lunar VSAT modules was dispatched together during each period, assuming that a single inverter is used to transmit the power from each group to another bus. Separate groups of lunar VSAT modules were left free to dispatch separately. Such a grouping is represented as can be seen in Figure 2. The thermal limit for single transmission lines were also assumed to be 100 kVA. The primary code for the energy storage simulation for a single-VSAT, single-base setup and a triple-VSAT, triple-base setup are given in the Appendix.

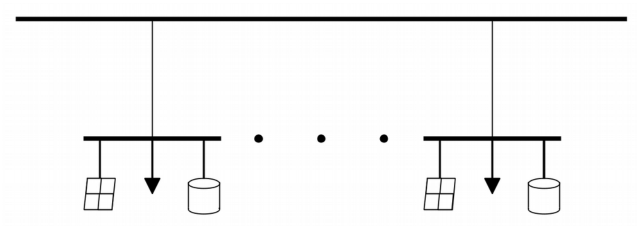

Fig. 2. Visualization of a grouping of individual lunar VSAT modules.

In order to maintain time independence across schedules, the power storage solutions for both the lunar VSAT and the lunar base modules were required to be at the same capacity, that is, the power storage capacity at the end of the 4-day lunar night cycle was required to be the same as the initial power storage at the beginning of the schedule. To simulate the lunar night cycle, the lunar VSAT solar array power generation upper bound was set to zero. Another consideration is that because of the need for safety and margin, both the lunar base power storage and the lunar VSAT module power storage were required to be at maximum capacity before the 4-day lunar night cycle began. The power charging, power discharging, and energy storage limits used for each lunar VSAT solar array module and each lunar base module are given in Table 2 and Table 3, respectively. The calculations for the maximum energy storage are presented in the next section of this research.

TABLE 2
Energy Storage-Related Limits for a Lunar VSAT Module

$P_{SC\text{-}MAX}$	100 W
$P_{SC\text{-}MIN}$	0 W
$P_{SD\text{-}MAX}$	100 W
$P_{SD\text{-}MIN}$	0 W
$E_{S\text{-}MAX}$	10.78 kWh
$E_{S\text{-}MIN}$	0 kWh

TABLE 3
Energy Storage-Related Limits for a Lunar Base Module

$P_{SC\text{-}MAX}$	100 kW
$P_{SC\text{-}MIN}$	0 kW
$P_{SD\text{-}MAX}$	100 kW
$P_{SD\text{-}MIN}$	0 kW
$E_{S\text{-}MAX}$	3.33 MWh
$E_{S\text{-}MIN}$	0 MWh

V. NUMERICAL RESULTS

The power requirements of a lunar VSAT solar array module and a lunar base module were used to deduce the power storage requirements. With a lunar VSAT solar array module having the specifications as seen in Table 4 and the load from Table 1, the power storage requirement can be found using (1). The round-trip efficiency estimate for such a small-scale battery was obtained from [10]. The power storage requirement for a lunar VSAT solar array module was calculated to be approximately 10.78 kWh.

TABLE 4
Power Budget Specifications for a Lunar VSAT Module

T	96 hours
η	0.98
μ	0.1
E_S	10.78 kWh

Similarly, with a lunar base module having the specifications as seen in Table 5 and the night-time load from Table 1, the power storage requirement can be found using (1). The round-trip efficiency estimate for such a large-scale battery was obtained from [9]. The power storage requirement for a lunar base module was calculated to be approximately 3.33 MWh.

TABLE 5
Power Budget Specifications for a Lunar Base Module

T	96 hours
η	0.90
μ	0.25
E_S	3.33 MWh

A. Case Description

Three different lunar microgrid architectures were considered. Case 1 is shown in Figure 3, which consists of 1 lunar VSAT group and 1 lunar base module. Case 2 is shown in Figure 4, which consists of 3 series-connected lunar VSAT groups connected to 3 series-connected lunar base modules via a single transmission line. Finally, Case 3

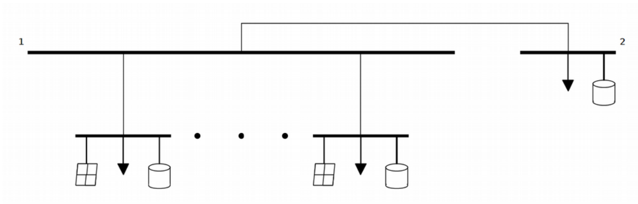

Fig. 3. Visualization of a lunar microgrid with 1 lunar VSAT group and 1 lunar base module.

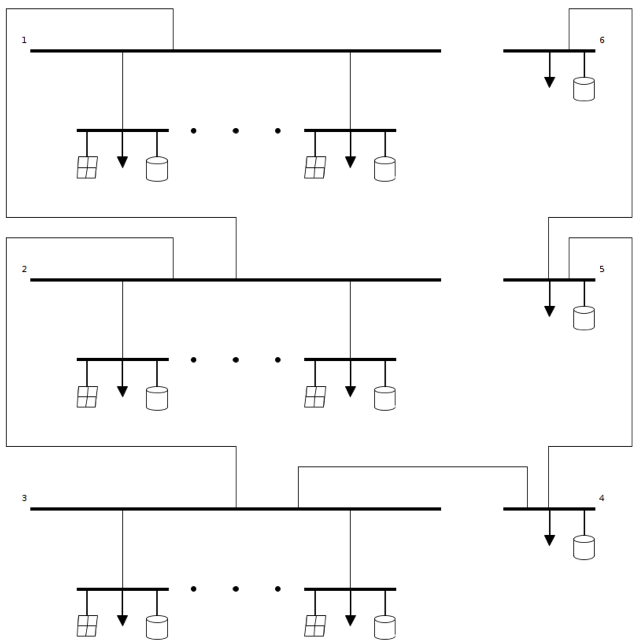

Fig. 4. Visualization of a lunar microgrid with 3 series-connected lunar VSAT groups connected to 3 series-connected lunar base modules via a single transmission line.

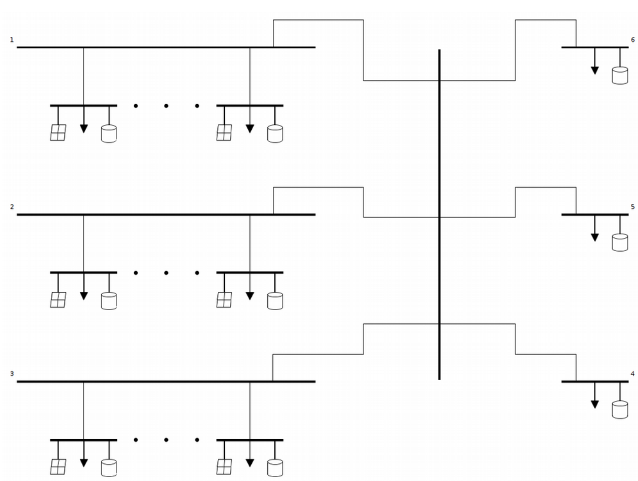

Fig. 5. Visualization of a lunar microgrid with 3 parallel-connected lunar VSAT groups connected to 3 parallel-connected lunar base modules.

is shown in Figure 5, which consists of 3 parallel-connected lunar VSAT groups connected to 3 parallel-connected lunar base modules.

B. Results – Energy Storage

For case 1, the linear programming optimization for the energy storage simulation yielded the dispatch scheduling for the single lunar VSAT group and the single lunar base module in Table 6 and Table 7, respectively. Period 7 is the 4-day lunar night. Note that for the lunar VSAT group, Table 6 lists the scheduled dispatch as the total from the group, since the group is dispatched together. Individual lunar VSAT module dispatches can be calculated by dividing these totals by the number of modules in a group.

Of note is that the optimization chose to charge the battery of the lunar VSAT group mostly in the period before the 4-day lunar night, and the optimization also chose to charge the battery of the lunar base module the two periods before the 4-day lunar night.

For a triple lunar VSAT group combined with triple lunar base modules, which represents case 2 and case 3, the energy storage simulation optimization is the same, as the simulation does not take into account losses that would result from the different architectures. The results of the linear programming optimization for a triple VSAT group combined with triple lunar base modules is shown below. Table 8, Table 9, and Table 10 correspond to the lunar VSAT groups at bus 1, at bus 2, and at bus 3, respectively. Table 11, 12, and 13 correspond to the lunar base modules at bus 4, bus 5, and bus 6, respectively. Note that during period 7 (the 4-day lunar nigh), the lunar VSAT groups were treated as being disconnected from the main grid so as not to use any power from the lunar base module batteries, but the lunar base module batteries were free to share power between the bases. That is, during period 7, the lunar base modules were left connected together while the lunar VSAT groups were each standalone.

Of note is that the optimization chose not to use the lunar VSAT groups evenly, instead using the groups at bus 2 and 3 to supply most of the power generation in period 1 through period 4, with the lunar VSAT group at bus 1 only using its maximum power generation output starting in period 5 and lasting through period 6. The optimization also chose to bring the battery of the lunar base module at bus 4 to its maximum capacity in period 5, while the batteries of the lunar base modules at bus 5 and bus 6 were not brought to maximum capacity until period 6. Also, since the lunar base modules were connected and sharing power during the lunar night cycle, the optimization chose not to use the batteries from the modules evenly, instead using all of the battery capacity from the lunar base modules at bus 4 and bus 5 to provide power during the lunar night while only using some of the battery capacity of the lunar base module at bus 6.

TABLE 6
Dispatch Schedule for the Lunar VSAT Group in Case 1

Period	P_G (kW)	P_{SC} (W)	P_{SD} (W)	E_S (kWh)
1	75.90	0	0	9.743
2	75.90	0	0	9.743
3	75.90	0	0	9.743
4	76.40	18.37	0	11.488
5	90.00	0	0	11.488
6	90.00	900.0	0	97.02
7	0	0	90.00	9.743

TABLE 7
Dispatch Schedule for the Lunar Base Module in Case 1

Period	P_{SC} (kW)	P_{SD} (kW)	E_S (kWh)
1	0	0	800.2
2	0	0	800.2
3	0	0	800.2
4	0.4778	0	843.7
5	14.10	0	2128.0
6	13.20	0	3330.0
7	0	25.00	800.2

TABLE 8
Dispatch Schedule for the Lunar VSAT Group at Bus 1

Period	P_G (kW)	P_{SC} (W)	P_{SD} (W)	E_S (kWh)
1	47.70	0	0	9.743
2	49.19	0	0	9.743
3	47.70	0	0	9.743
4	47.70	0	0	9.743
5	90.00	18.37	0	11.49
6	90.00	900.0	0	97.02
7	0	0	900.0	9.743

TABLE 9
Dispatch Schedule for the Lunar VSAT Group at Bus 2

Period	P_G (kW)	P_{SC} (W)	P_{SD} (W)	E_S (kWh)
1	90.00	0	0	9.743
2	90.00	0	0	9.743
3	90.00	0	0	9.743
4	90.00	0	0	9.743
5	90.00	18.37	0	11.49
6	90.00	900.0	0	97.02
7	0	0	900.0	9.743

TABLE 10
Dispatch Schedule for the Lunar VSAT Group at Bus 3

Period	P_G (kW)	P_{SC} (W)	P_{SD} (W)	E_S (kWh)
1	90.00	0	0	9.743
2	90.00	0	0	9.743
3	90.00	0	0	9.743
4	90.00	0	0	9.743
5	90.00	18.37	0	11.49
6	90.00	900.0	0	97.02
7	0	0	900.0	9.743

TABLE 11
Dispatch Schedule for the Lunar Base Module at Bus 4

Period	P_{SC} (kW)	P_{SD} (kW)	E_S (kWh)
1	0	0	0
2	1.488	0	135.6
3	0	0	135.6
4	0	0	135.6
5	35.08	0	3330
6	0	0	3330
7	0	32.91	0

TABLE 12
Dispatch Schedule for the Lunar Base Module at Bus 5

Period	P_{SC} (kW)	P_{SD} (kW)	E_S (kWh)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	7.170	0	653.0
6	29.39	0	3330
7	0	32.91	0

TABLE 13
Dispatch Schedule for the Lunar Base Module at Bus 6

Period	P_{SC} (kW)	P_{SD} (kW)	E_S (kWh)
1	0	0	2401
2	0	0	2401
3	0	0	2401
4	0	0	2401
5	0	0	2401
6	10.21	0	3330
7	0	9.185	2401

C. Results – Contingency Analysis

This section presents the results of contingency analysis for the cases presented above, and also discusses possible recovery actions as well as mitigation strategies for each contingency. Note that this analysis will not be extensive, and instead will focus on a few worst-case scenarios.

1) Case 1:

For case 1, contingency analysis was performed using the dispatch schedule from Table 6 and Table 7. Failure of a lunar VSAT module solar array during either period 5 or period 6 would be the worst-case for this contingency, as this is when the optimization chose to maximize the power generation of the lunar VSAT group in order to charge the batteries. This was done by setting the power generation upper bound for the lunar VSAT group to be 80 kW instead of the standard 90 kW, simulating the loss of a single solar array within the group. With no recovery actions, the optimization fails to converge, which means it is not feasible to meet the power requirements. However, even reducing the load of the lunar base by 10 kW, the optimization is able to converge to a solution. Because the lunar base is expected to need only 25 kW of power during the 4-day lunar night, it is expected that a power reduction from 75 kW to 65 kW in an emergency situation during the day is feasible, making this a viable recovery action. Mitigation strategies include (i) increasing the number of individual lunar VSAT modules in a group, (ii) having a spare lunar VSAT module that is able to be deployed immediately, and (iii) forcing the optimization to charge the batteries sooner rather than later.

Failure of a lunar VSAT module battery either period 6 or period 7 would be the worst-case for this contingency, as the optimization chose to charge the lunar VSAT batteries primarily in period 6 and the power for the lunar VSAT electronics during period 7 is provided entirely by the lunar VSAT batteries.

To simulate loss of a lunar VSAT module battery in period 6, the total charging upper bound for the lunar VSAT group was reduced from 900 W to 800 W. The requirement that the lunar VSAT module battery be at its maximum capacity by the end of period 6 was also removed, as was the requirement that the final capacity and the initial capacity of the lunar VSAT module battery be equivalent. Finally, the total battery capacity for the lunar VSAT group was set to 87.52 kWh instead of the nominal 97.02 kWh, as while 8 of the 9 batteries would be able to fully charge, the 9th battery would remain at the capacity it had by the end of period 5. This contingency also caused the optimization to fail, as even though there would be enough energy storage within the lunar VSAT group to survive the 4-day lunar night, each battery within a single lunar VSAT module is limited to only discharging 100 W of power. Mitigation strategies include (i) having a spare lunar VSAT module that is able to be deployed immediately and (ii) forcing the optimization to charge the batteries sooner rather than later.

To simulate the loss of a lunar VSAT module battery in period 7, the total discharging upper bound for the lunar VSAT group was reduced from 900 W to 800 W. The requirement that the final capacity and the initial capacity of the lunar VSAT module battery be equivalent was also removed. With this contingency, the optimization also failed, as the discharging upper bound of 800 W is insufficient to provide the 900 W of load for the lunar VSAT group during the 4-day lunar night when no local power generation is active. A possible recovery action is to disable the faulty individual lunar VSAT module, as this would reduce the load for the lunar VSAT group from 900 W to 800 W. A mitigation strategy would be to size the discharge rate of an individual lunar VSAT module such that when it is withing group, the loss of one battery's ability to discharge does not result in the inability to provide the full 900 W of power. That is, if the discharge upper bound were designed to be 112.5 W per lunar VSAT module instead of 100 W per lunar VSAT module, the group would still be capable of providing the 900 W of power needed.

If the transmission line linking bus 1 and bus 2 were to fail during period 5 or period 6, not only would the lunar base not be able to charge its battery enough to survive the 4-day lunar night, but even considering the recovery action of reducing the power needed from 75 kW to 25 kW, the lunar base would run out of power before the end of the period. This contingency, while it does not have any viable recovery actions, does have the mitigation strategies of (i) having 2 transmission lines connect the lunar VSAT group to the lunar base and (ii) forcing the optimization to charge the battery sooner rather than later.

Failure of the lunar base battery during period 5 or 6 would be the worst-case for this contingency since the optimization chose to charge the battery primarily during these periods. To simulate the loss of the lunar base battery during period 5, the following changes were made to the simulation: (i) the total charging upper bound for the lunar base battery was set to 0, (ii) the requirement that the lunar base battery be at maximum capacity by the end of period 6 was removed, and (iii) the requirement that the initial and final capacities of the lunar base batter be equivalent was removed. The optimization fails to converge, as there is not enough power generation available in period 6 to charge the lunar base battery enough to survive the 4-day lunar night, even considering completely charging the lunar VSAT group batteries in period 5. A recover action of reducing the lunar base power requirements during period 6 from 75 kW to 25 kW also results in the optimization failing, though this is suspected to be a calculation error. Given the dispatch schedule is followed from period 1 through period 4, the total energy storage in the lunar base battery will be approximately 843.7 kWh. If the lunar VSAT group batteries are charged completely in period 5, and the lunar base load is reduced to 25 kW during period 6 after the contingency is fixed, the lunar VSAT group would still be able to provide a net power generation of approximately 64.10 kW to the lunar base battery, or an increase in capacity of 60.81 kW after accounting for charging inefficiency. This would be more than enough to charge the lunar base battery to its maximum capacity solely within period 6. Mitigation strategies include having multiple batteries with the lunar base module that split the total energy storage requirement, as this would allow most of the batteries to charge while a single one cannot charge. Another mitigation strategy is forcing the optimization to charge the batteries sooner rather than later.

If the lunar base battery fails during period 6, the lunar base would enter the 4-day lunar night with only 2128 kWh of energy storage, which is insufficient to provide 25 kW of power to the lunar base through the 4-day lunar night. There are no viable recovery actions, though mitigating this contingency by forcing the optimization to charge the batteries sooner rather than later is an option.

2) Case 2:

For case 2, contingency analysis was performed using the dispatch schedule from Tables 8 through 13. Also note that because of the microgrid architecture for this particular case, a few considerations for the transmission lines have to be acknowledged. Specifically, instead of the standard 100 kVA thermal limit for transmission lines, (i) the thermal limit for the link between bus 2 and 3 would have to be 200 kVA, (ii) the thermal limit for the link between bus 3 and bus 4 would have to be 300 kVA, and (iii) the thermal limit for the link between bus 4 and bus 5 would have to be 200 kVA, all solely for allowing the power generation from the 3 lunar VSAT groups to reach the lunar base at bus 6. Additionally, to account for the lunar bases being able to share power, the thermal limit for the link between bus 5 and bus 6 would have to be 200 kVA.

Failure of a lunar VSAT solar array module during either period 5 or period 6 would equally affect all of the lunar VSAT groups, as the power generation for these is at its peak during these periods. To simulate the loss of a lunar VSAT battery during either period 5 or period 6, the following changes were made to the simulation: (i) the power generation upper bound for the lunar VSAT group at bus 1 was reduced from 90 kW to 80 kW, (ii) the requirements that the lunar VSAT group batteries at bus 1 be at their maximum capacity by the end of period 6 was removed, and (iii) the requirement that the final capacity and the initial capacity of the lunar VSAT group batteries at bus 1 be equivalent was removed. Similar to case 1, a recovery action of reducing the load of a lunar base by 10 kW, the optimization is able to converge to a solution. Mitigation strategies include (i) increasing the number of individual lunar VSAT modules in a group, (ii) having a spare lunar VSAT module that is able to be deployed immediately, and (iii) forcing the optimization to charge the batteries sooner rather than later.

If a single lunar VSAT module battery were to fail during period 6, similar issues arise in case 2 as in case 1, namely that the simulation fails to converge even after removing the requirement that the batteries for the lunar VSAT group at bus 1 be at maximum capacity by the end of period 6 and the requirement that initial and final capacities for the batteries for the lunar VSAT group at bus 1 be equivalent. This is because even though there would be enough energy storage within the lunar VSAT group to survive the 4-day lunar night, each battery within a single lunar VSAT module is limited to only discharging 100 W of power. If a single lunar VSAT module battery were to fail during period 7, the optimization again fails due to the limited discharging capacity of each individual lunar VSAT module. Mitigation strategies are the same as for case 1, namely that the discharge capacity for an individual lunar VSAT module should be 112.5 W instead of 100 W.

Depending on the specific implementation of case 2, with respect to whether the 200 kVA and 300 kVA lines are monolines with the full thermal limit or are individual lines each with a 100 kVA limit, the contingency analysis results for a failed transmission line are different for case 2. If the transmission line connected bus 3 and bus 4 were to be a single 300 kVA line, this would be the worst-case for a transmission line contingency during period 6, as the lunar base modules would not only not be able to charge their batteries sufficiently to survive the 4-day lunar night, the lunar base batteries would completely deplete before the end of period 6. There are no viable recover actions for this contingency. The primary mitigation strategy would be to ensure that the transmission line connecting bus 3 to bus 4 is at least 2 separate lines instead of a single line, but similarly as before forcing the optimization to charge the batteries sooner rather than later would work.

If the connection between bus 3 and bus 4 were to be a group of three 100 kVA lines, a contingency of one of these lines going out during period 6 would still cause the simulation not to converge, as the power generation would then be limited to 200 kW instead of the 270 kW scheduled during this period. This does mean, however, that a recovery action of reducing the total lunar base power usage by 70 kW would result in the simulation converging, as the batteries for the lunar base modules would still be able to charge to their maximum capacity before the 4-day lunar night. Mitigation strategies include the addition of another 100 kVA transmission line between bus 3 and bus 4, as well as forcing the optimization to charge the batteries sooner than later.

Failure of a single 200 kVA transmission line between bus 4 and bus 5 during period 5 is another major contingency, as this would result in the batteries in both the lunar base modules at bus 5 and bus 6 not to be able to charge during this time. While the battery in the lunar base module at bus 4 would still be able to charge completely, the batteries in the lunar modules at bus 5 and bus 6 would be completely depleted before the end of the period even after reducing the power requirement for each of the disconnected bases to 25 kW each. The primary mitigation strategy for this contingency is to have the transmission line connecting bus 4 to bus 5 to be at least 2 separate lines instead of a single line, but similarly as before forcing the optimization to charge the batteries sooner rather than later would work.

If the connection between bus 4 and bus 5 were to be two 100 kVA lines, a contingency of one of these lines going out during period 5 would still cause the optimization not to converge without recovery actions, as the power requirement of the lunar modules at bus 5 and bus 6 total to over 150 kW, which is greater than the 100 kVA limit for the remaining line between bus 4 and bus 5. However, if the recovery action of reducing the power requirement of both lunar modules at bus 5 and bus 6 from 75 kW each to 25 kW each, the total flow in the remaining line between bus 4 and bus 5 would be less than the 100 kVA limit even when accounting for following the original charging schedule during this period. Mitigation strategies include the addition of another 100 kVA transmission line between bus 4 and bus 5, as well as forcing the optimization to charge the batteries sooner than later.

Failure of a single lunar base module battery during either period 6 or period 7 would be the worst case of this contingency for case 2. If a battery fails during period 6, the worst bus for this to happen on would be for the lunar base at bus 5, since it is charging the most during this period. The result of this would be that the total energy stored for the lunar base modules going into period 7 would be approximately 7313 kWh, just shy of the minimum 7590 kWh needed for all 3 lunar base modules to survive the 4-day lunar night. There are no valid recovery actions for this, as reducing power consumption of the lunar bases during period 6 would not make the battery at bus 5 charge any more. Similar to this contingency in case 1, mitigation strategies include having multiple batteries with the lunar base module that split the total energy storage requirement, as this would allow most of the batteries to charge while a single one cannot charge. Another mitigation strategy is forcing the optimization to charge the batteries sooner rather than later.

If a lunar base module battery fails during period 7, the remaining 6660 kWh of energy storage being shared between the bases would not be enough to cover the minimum 7590 kWh of energy needed to survive the 4-day lunar night. There are no valid recovery actions for this contingency. The primary mitigation strategy would be to have multiple batteries with the lunar base module that split the total energy storage requirement so that a contingency of a single lunar base module battery doesn't make the entire 3330 kWh of energy stored suddenly unavailable.

3) Case 3:

For case 3, contingency analysis was performed using the dispatch schedule from Tables 8 through 13. Failure of a single lunar VSAT module solar array is similar to this same contingency in case 2, namely that loss of a solar array during either period 5 or period 6 would affect all of the lunar VSAT group equally since their power generation has the same dispatch during these periods. Similar to case 1, a recovery action of reducing the load of a lunar base by 10 kW, the optimization is able to converge to a solution. Mitigation strategies include (i) increasing the number of individual lunar VSAT modules in a group, (ii) having a spare lunar VSAT module that is able to be deployed immediately, and (iii) forcing the optimization to charge the batteries sooner rather than later.

If a single lunar VSAT module battery were to fail during period 6, case 2 has a similar outcome to case 3, namely that the optimization would fail to converge due to the lack of discharge capability of the individual lunar VSAT module batteries despite the energy storage total for the lunar VSAT group being enough to survive the 4-day lunar night. If a single lunar VSAT module battery were to fail during period 7, again the limiting factor would be the discharge rate of the individual lunar VSAT batteries. Mitigation strategies include increasing the discharge capacity for an individual lunar VSAT module from 112.5 W to 100 W.

Failure of a transmission line in case 3 is similar to when this happens in case 2, namely that the worst-case scenario for this happening is during period 6 or period 7. For case 2, period 6 is the worst-case if a transmission line linking any of the lunar VSAT groups to the central bus goes out, while period 7 is the worst case if a transmission line linking any of the lunar base modules to the central bus goes out. If a transmission line connecting a lunar VSAT group to the central bus were to go out in period 6, the 270 kW schedule during this period would be limited to 200 kW when using this to provide power to the lunar bases and to charge the batteries of the lunar bases. However, a recovery action of reducing the total lunar base power consumption by 70 kW would allow the batteries for the lunar bases to charge according to the original schedule. Mitigation strategies including providing an extra 100 kVA line between each lunar VSAT group and the central bus. If a transmission line connecting a lunar base module to the central bus were to go out in period 7, this would actually not have any adverse side effects, as each lunar base would be able to provide its own power from the 3330 kWh energy storage it acquired by the end of period 6. No mitigation strategy is needed for this contingency. if a transmission line connecting the lunar base module at bus 5 to the central bus were to go out in period 6, the optimization would be unable to converge, as even with an inviable recovery action of reducing power consumption at the lunar base at bus 5 to 0 kW, the total lunar base energy storage by the end of period 6 would only be 7313 kWh, just shy of the 7590 kWh of energy needed to survive the 4-day lunar night. Mitigation strategies including providing an extra 100 kVA line between each lunar base module and the central bus.

Failure of a lunar base module battery in case 3 is of similar severity as in case 2, again for the primary reason that 6660 kWh of storage is not enough for 3 lunar base modules to survive the lunar night. There are no valid recovery actions for this contingency. The primary mitigation strategy would be to have multiple batteries with the lunar base module that split the total energy storage requirement so that a contingency of a single lunar base module battery doesn't make the entire 3330 kWh of energy stored suddenly unavailable.

D. Discussion

The most problematic issues with the 3 cases presented include the following, in no particular order: (i) the power discharge rate of an individual lunar VSAT module cannot handle the contingency of a single lunar VSAT battery going out during period 7, (ii) loss of a transmission line often leads to inability to meet the schedule provided by the optimization, and (iii) failure of a single lunar VSAT battery results in the inability of the base to meet its minimum power requirements. Specific to cases 2 and 3, while the contingency of a single lunar VSAT solar array going out does not initially cause problems, the limiting factor is that the optimization schedule the majority of the battery charging to occur in the periods immediately prior to the 4-day lunar night, leaving little room for recovery.

A simple fix to solving the issue arising from a contingency of a single lunar VSAT module battery going out is to have the discharge limit be increased from 100 W to 112.5 W during the design phase of the hardware. This would allow for a single lunar VSAT module battery to go out in each lunar VSAT group without the need for recovery actions.

In order to stifle the need for recovery actions after a transmission line outage, the optimization can be updated to charge the batteries as soon as possible after the 4-day lunar night is over, either by incentivizing charging of the batteries or by requiring the batteries to be at maximum capacity some time before period 6. This was an oversight initially, as it was thought that penalizing the discharging of batteries was equivalent to incentivizing the charging of batteries, but the optimization that MATLAB performs seems to indicate otherwise. Forcing the optimization in this way would also solve the problem of losing a single VSAT solar array in cases 2 and 3, as the limiting factor here was again the schedule from the optimization dictating that the bulk of battery charging occur in the period immediately prior to the 4-day lunar night.

This research modeled the battery within a lunar base module as a single 3330 kWh battery, while in reality this would likely be a group of smaller capacity batteries as is common when designing electrical and electronic circuits. Recovery actions for loss of a single lunar base module battery can be done away with if the large mono-battery is instead many smaller capacity batteries, as loss of a single battery would not mean loss of 3330 kWh of storage.

With regards to mitigation strategies, the most common fix for various outages was to include more transmission lines between various points initially. This would solve the single transmission line contingency of case 1, as well as all transmission line contingencies in case 2 and case 3. In this regard, comparison of the architecture presented in case 2 and the architecture presented in case 3 can be compared. While the above mitigation strategies that stifle recovery actions are valid, a likely desired mitigation strategy would be to include these extra transmission lines between all points. If only 100 kVA transmission lines are used to connect buses, the architecture in case 2 would required 9 transmission lines in the nominal case, while the architecture in case 3 would require 6 transmission lines in the nominal case. If a single 100 kVA transmission line is added between each connection, the architecture in case 2 would now require 14 transmission lines, and the architecture in case 3 would now require 12 transmission lines. It can be seen that with respect to implementing additional transmission lines, case 3 is superior solely from the standpoint of requiring less resources, which is a major consideration for human spaceflight missions. It is also noteworthy to point out that while in the nominal case 2 when considering only 100 kVA transmission lines, there are 6 possible contingencies that would cause loss of full power generation, while in the nominal case 3 there are only 3 possible contingencies that would cause loss of full power generation.

VI. CONCLUSIONS

This research did not consider losses in the different architecture cases, though this could be applied in the future. Specifically, the flow from the reference bus into the system must be equal to the sum of the flows on the lines connected to the reference. With this, the change in power injection from the reference bus is equal to the change in the flows of the lines adjacent to the reference bus. Since a generation injecting power into the system that is balance by the reference bus is the same as a power transfer from the generator to the reference bus, the change in system losses with respect to the change in power injected from the generator is equal to 1 plus the sum of the power transfer distribution factor in all of the lines in the system for a power transfer from the generator to the reference bus1.

While many papers have detailed the power generation or power consumption requirements of a lunar base under various conditions, this research focuses on comparing different lunar microgrid architectures. Though there were several different mitigation strategies that would individually stifle the need for recovery actions, it is likely that all of these mitigation strategies would be implemented together since consideration of safety is the primary factor in human spaceflight missions.

The architecture presented in case 3 seems to be better than the architecture presented in case 2 when considering the amount of required resources and the way in which contingencies are handled, as well as with respect to the number of transmission line contingencies that are possible. While this work is not conclusive, it does indicate that lunar microgrid architectures that are somehow parallelized are superior to those that rely on a single string of buses, similar to how the power transmission systems offer better contingency handling than power distribution systems.

VII. APPENDIX

A. MATLAB Code for a Single-VSAT, Single-Base Lunar Microgrid Architecture

```
format shortG

vsat_size = 9;
Pd2 = [75 75 75 75 75 75 25]';
n = size(Pd2,1);
Pd1 = 0.1 * vsat_size * ones(n, 1);

eff1 = sqrt(0.98);
Pg1_max = 10 * vsat_size;
Psc1_max = 0.1 * vsat_size;
Psd1_max = 0.1 * vsat_size;
Es1_max = 10.78 * vsat_size;

eff2 = sqrt(0.9);
Psc2_max = 100;
Psd2_max = 100;
Es2_max = 3330;

period_hours = 4 * 24;
cont_margin = 0.001;

% penalize discharging
f = [
    zeros(n,1); % Pg1(1..T)
    zeros(n,1); % Psc1(1..T)
    ones(n,1); % Psd1(1..T)
    zeros(n,1); % Psc2(1..T)
    ones(n,1); % Psd2(1..T)
    zeros(n+1,1); % Es1(0..T)
    zeros(n+1,1); % Es2(0..T)
];

Aeq = zeros(3*n+4+1+1, 7*n+2);
for i = 1:n
    % power balance
    if i < n
        % Pg1(t) - Psc1(t) + Psd1(t) - Psc2(t)
+ Psd2(t)
        Aeq(i, i) = 1; % Pg1(t)
        Aeq(i, i+n) = -1; % Psc1(t)
        Aeq(i, i+2*n) = 1; % Psd1(t)
        Aeq(i, i+3*n) = -1; % Psc2(t)
        Aeq(i, i+4*n) = 1; % Psd2(t)
    else
        % this equation will end up as 0 = 0
since I don't want to rewrite the code
    end

    % energy balance
     % Es1(t) - Es1(t-1) - period n1 Psc1(t) +
period (1/n1) Psd1(t)
    Aeq(i+n, i+5*n+1) = 1; % Es1(t)
    Aeq(i+n, i+5*n) = -1; % Es1(t-1)
      Aeq(i+n, i+n) = period_hours * -eff1; %
Psc1(t)
     Aeq(i+n, i+2*n) = period_hours * 1/eff1; %
Psd1(t)

    % energy balance
     % Es2(t) - Es2(t-1) - period n2 Psc2(t) +
period (1/n2) Psd2(t)
    Aeq(i+2*n, i+6*n+1+1) = 1; % Es2(t)
    Aeq(i+2*n, i+6*n+1) = -1; % Es2(t-1)
    Aeq(i+2*n, i+3*n) = period_hours * -eff2; %
Psc2(t)
     Aeq(i+2*n, i+4*n) = period_hours * 1/eff2;
% Psd2(t)
end;

% Es1(0) - Es1(T) = 0;
Aeq(3*n+1, 5*n+1) = 1; Aeq(3*n+1, 6*n+1) = -1;
% Es1(6) = Es1-max
Aeq(3*n+2, 5*n+1+6) = 1;

% Es2(0) - Es2(T) = 0;
Aeq(3*n+3, 6*n+1+1) = 1; Aeq(3*n+3, 7*n+1+1) =
-1;
% Es2(6) = Es2-max
Aeq(3*n+4, 6*n+1+1+6) = 1;

% lunar VSAT modules disconnected from grid
% Pg1(T) - Psc1(T) + Psd1(T) = Pd1(T)
Aeq(3*n+5,  n)  =  1;  Aeq(3*n+5,  2*n)  =  -1;
Aeq(3*n+5, 3*n) = 1;

% lunar base module (standalone)
% -Psc2(T) + Psd2(T) = Pd2(T)
Aeq(3*n+6, 4*n) = -1; Aeq(3*n+6, 5*n) = 1;

beq = [
    (Pd1(1:n-1) + Pd2(1:n-1)); % power balance
    0; % placeholder

    zeros(2*n,1); % energy balance

    0; % Es1(0) - Es1(T) = 0;
    Es1_max; % Es1(6) = Es1-max
    0; % Es2(0) - Es2(T) = 0;
    Es2_max; % Es2(6) = Es2-max

    % lunar VSAT modules disconnected from grid
    % Pg1(T) - Psc1(T) + Psd1(T) = Pd1(T)
    Pd1(n);

    % lunar base module (standalone)
    % -Psc2(T) + Psc2(T) = Pd2(T)
    Pd2(n);
];

lb = [
    zeros(n,1); % Pg1(1..T)
    zeros(n,1); % Psc1(1..T)
    zeros(n,1); % Psd1(1..T)
    zeros(n,1); % Psc2(1..T)
```

```
    zeros(n,1); % Psd2(1..T)
    zeros(n+1,1); % Es1(0..T)
    zeros(n+1,1); % Es2(0..T)
];
ub = [
    Pg1_max * ones(n-1,1); % Pg1(1..6)
    0; % Pg1(7)
    Psc1_max * ones(n,1); % Psc1(1..T)
    Psd1_max * ones(n,1); % Psd1(1..T)
    Psc2_max * ones(n,1); % Psc2(1..T)
    Psd2_max * ones(n,1); % Psd2(1..T)
    Es1_max * ones(n+1,1); % Es1(0..T)
    Es2_max * ones(n+1,1); % Es2(0..T)
];

x = linprog(f, [], [], Aeq, beq, lb, ub);

Pg1 = x(1:n);
Psc1 = x(n+1:2*n);
Psd1 = x(2*n+1:3*n);

Psc2 = x(3*n+1:4*n);
Psd2 = x(4*n+1:5*n);

Es1 = x(5*n+1:6*n+1);
Es2 = x(6*n+2:7*n+2);
```

B. MATLAB Code for a Triple-VSAT, Triple-Base Lunar Microgrid Architecture

```
format shortG

vsat_size = 9;
period_hours = 4 * 24;
cont_margin = 0.001;

Pd4 = [75 75 75 75 75 75 25]';
Pd5 = Pd4;
Pd6 = Pd4;
n = size(Pd4,1);
Pd1 = 0.1 * vsat_size * ones(n,1);
Pd2 = Pd1;
Pd3 = Pd1;

eff1 = sqrt(0.98);
Pg1_max = 10 * vsat_size;
Psc1_max = 0.1 * vsat_size;
Psd1_max = 0.1 * vsat_size;
Es1_max = 10.78 * vsat_size;

eff2 = sqrt(0.98);
Pg2_max = 10 * vsat_size;
Psc2_max = 0.1 * vsat_size;
Psd2_max = 0.1 * vsat_size;
Es2_max = 10.78 * vsat_size;

eff3 = sqrt(0.98);
Pg3_max = 10 * vsat_size;
Psc3_max = 0.1 * vsat_size;
Psd3_max = 0.1 * vsat_size;
Es3_max = 10.78 * vsat_size;

eff4 = sqrt(0.9);
Psc4_max = 100;
Psd4_max = 100;
Es4_max = 3330;

eff5 = sqrt(0.9);
Psc5_max = 100;
Psd5_max = 100;
Es5_max = 3330;

eff6 = sqrt(0.9);
Psc6_max = 100;
Psd6_max = 100;
Es6_max = 3330;

f = [
    zeros(n,1); % Pg1(1..T)
    zeros(n,1); % Psc1(1..T)
    ones(n,1); % Psd1(1..T)

    zeros(n,1); % Pg2(1..T)
    zeros(n,1); % Psc2(1..T)
    ones(n,1); % Psd2(1..T)

    zeros(n,1); % Pg3(1..T)
    zeros(n,1); % Psc3(1..T)
    ones(n,1); % Psd3(1..T)

    zeros(n,1); % Psc4(1..T)
    ones(n,1); % Psd4(1..T)

    zeros(n,1); % Psc5(1..T)
    ones(n,1); % Psd5(1..T)

    zeros(n,1); % Psc6(1..T)
    ones(n,1); % Psd6(1..T)

    zeros(n+1,1); % Es1(0..T)
    zeros(n+1,1); % Es2(0..T)
    zeros(n+1,1); % Es3(0..T)
    zeros(n+1,1); % Es4(0..T)
    zeros(n+1,1); % Es5(0..T)
    zeros(n+1,1); % Es6(0..T)
];

Aeq = zeros(7*n+(6*2)+3+1, 15*n+6*(n+1));
for i = 1:n;
    % % % % % % % % % % % % % % % % % %
    % power balance
    % % % % % % % % % % % % % % % % % %

    if i < n
        % Pg1(t) - Psc1(t) + Psd1(t)
        % + Pg2(t) - Psc2(t) + Psd2(t)
        % + Pg3(t) - Psc3(t) + Psd3(t)
        % + Psc4(t) + Psd4(t)
        % + Psc5(t) + Psd5(t)
        % + Psc6(t) + Psd6(t)
        % =
         % Pd1(t) + Pd2(t) + Pd3(t) + Pd4(t) +
Pd5(t) + Pd6(t)
        Aeq(i, i) = 1; % Pg1(t)
        Aeq(i, i+n) = -1; % Psc1(t)
        Aeq(i, i+2*n) = 1; % Psd1(t)

        Aeq(i, i+3*n) = 1; % Pg2(t)
        Aeq(i, i+4*n) = -1; % Psc2(t)
        Aeq(i, i+5*n) = 1; % Psd2(t)

        Aeq(i, i+6*n) = 1; % Pg3(t)
        Aeq(i, i+7*n) = -1; % Psc3(t)
        Aeq(i, i+8*n) = 1; % Psd3(t)

        Aeq(i, i+9*n) = -1; % Psc4(t)
        Aeq(i, i+10*n) = 1; % Psd4(t)
```

```
        Aeq(i, i+11*n) = -1; % Psc5(t)
        Aeq(i, i+12*n) = 1; % Psd5(t)

        Aeq(i, i+13*n) = -1; % Psc6(t)
        Aeq(i, i+14*n) = 1; % Psd6(t)
    else
         % this equation will end up as 0 = 0
since I don't want to rewrite the code
    end

    % % % % % % % % % % % % % % % % %
    % energy balance
    % % % % % % % % % % % % % % % % %

     % Es1(t) - Es1(t-1) - period n1 Psc1(t) +
period 1/n1 Psd1(t) = 0
    Aeq(i+n, i+15*n+1) = 1; % Es1(t)
    Aeq(i+n, i+15*n) = -1; % Es1(t-1)
     Aeq(i+n, i+1*n) = period_hours * -eff1; %
Psc1(t)
     Aeq(i+n, i+2*n) = period_hours * 1/eff1; %
Psd1(t)

     % Es2(t) - Es2(t-1) - period n2 Psc2(t) +
period 1/n2 Psd2(t) = 0
    Aeq(i+2*n, i+16*n+2) = 1; % Es2(t)
    Aeq(i+2*n, i+16*n+1) = -1; % Es2(t-1)
    Aeq(i+2*n, i+4*n) = period_hours * -eff2; %
Psc2(t)
     Aeq(i+2*n, i+5*n) = period_hours * 1/eff2;
% Psd2(t)

    % % Es3(t) - Es3(t-1) - period n3 Psc3(t) +
period 1/n3 Psd3(t) = 0
    Aeq(i+3*n, i+17*n+3) = 1; % Es3(t)
    Aeq(i+3*n, i+17*n+2) = -1; % Es3(t-1)
    Aeq(i+3*n, i+7*n) = period_hours * -eff3; %
Psc3(t)
     Aeq(i+3*n, i+8*n) = period_hours * 1/eff3;
% Psd3(t)

    % % Es4(t) - Es4(t-1) - period4n4 Psc4(t) +
period 1/n4 Psd4(t) = 0
    Aeq(i+4*n, i+18*n+4) = 1; % Es1(t)
    Aeq(i+4*n, i+18*n+3) = -1; % Es4(t-1)
    Aeq(i+4*n, i+9*n) = period_hours * -eff4; %
Psc4(t)
    Aeq(i+4*n, i+10*n) = period_hours * 1/eff4;
% Psd4(t)

    % % Es5(t) - Es5(t-1) - period n5 Psc5(t) +
period 1/n5 Psd5(t) = 0
    Aeq(i+5*n, i+19*n+5) = 1; % Es5(t)
    Aeq(i+5*n, i+19*n+4) = -1; % Es5(t-1)
     Aeq(i+5*n, i+11*n) = period_hours * -eff5;
% Psc5(t)
    Aeq(i+5*n, i+12*n) = period_hours * 1/eff5;
% Psd5(t)

    % % Es6(t) - Es6(t-1) - period n6 Psc6(t) +
period 1/n6 Psd6(t) = 0
    Aeq(i+6*n, i+20*n+6) = 1; % Es6(t)
    Aeq(i+6*n, i+20*n+5) = -1; % Es6(t-1)
     Aeq(i+6*n, i+13*n) = period_hours * -eff6;
% Psc6(t)
    Aeq(i+6*n, i+14*n) = period_hours * 1/eff6;
% Psd6(t)
end;
% Es1(0) - Es1(T) = 0
Aeq(7*n+1, 15*n+1) = 1; Aeq(7*n+1, 16*n+1) =
-1;
% Es1(6) = Es1_max
Aeq(7*n+2, 15*n+1+6) = 1;

% Es2(0) - Es2(T) = 0
Aeq(7*n+3, 16*n+2) = 1; Aeq(7*n+3, 17*n+2) =
-1;
% Es2(6) = Es2-max
Aeq(7*n+4, 16*n+2+6) = 1;

% Es3(0) - Es3(T) = 0
Aeq(7*n+5, 17*n+3) = 1; Aeq(7*n+5, 18*n+3) =
-1;
% Es3(6) = Es3-max
Aeq(7*n+6, 17*n+3+6) = 1;

% Es4(0) - Es4(T) = 0
Aeq(7*n+7, 18*n+4) = 1; Aeq(7*n+7, 19*n+4) =
-1;
% Es4(6) = Es4-max
Aeq(7*n+8, 18*n+4+6) = 1;

% Es5(0) - Es5(T) = 0
Aeq(7*n+9, 19*n+5) = 1; Aeq(7*n+9, 20*n+5) =
-1;
% Es5(6) = Es5-max
Aeq(7*n+10, 19*n+5+6) = 1;

% Es6(0) - Es6(T) = 0
Aeq(7*n+11, 20*n+6) = 1; Aeq(7*n+11, 21*n+6) =
-1;
% Es6(6) = Es6-max
Aeq(7*n+12, 20*n+6+6) = 1;

% lunar VSAT modules disconnected from grid
% Pg1(T) - Psc1(T) + Psd1(T) = Pd1(t)
Aeq(7*n+13, n) = 1; Aeq(7*n+13, 2*n) = -1;
Aeq(7*n+13, 3*n) = 1;
% Pg2(T) - Psc2(T) + Psd2(T) = Pd2(t)
Aeq(7*n+14, 4*n) = 1; Aeq(7*n+14, 5*n) = -1;
Aeq(7*n+14, 6*n) = 1;
% Pg3(T) - Psc3(T) + Psd3(T) = Pd3(t)
Aeq(7*n+15, 7*n) = 1; Aeq(7*n+15, 8*n) = -1;
Aeq(7*n+15, 9*n) = 1;

% lunar base modules share power
% -Psc4(T) + Psd4(T) - Psc5(T) + Psd5(T) -
Psc6(T) + Psd6(T) = Pd4(T) + Pd5(T) + Pd6(T)
Aeq(7*n+16, 10*n) = -1; Aeq(7*n+16, 11*n) = 1;
Aeq(7*n+16, 12*n) = -1; Aeq(7*n+16, 13*n) = 1;
Aeq(7*n+16, 14*n) = -1; Aeq(7*n+16, 15*n) = 1;

beq = [
    % power balance
      (Pd1(1:n-1) + Pd2(1:n-1) + Pd3(1:n-1) +
Pd4(1:n-1) + Pd5(1:n-1) + Pd6(1:n-1))
    % placeholder
    0;

    zeros(6*n,1); % energy balance

    0; % Es1(0) - Es1(T) = 0
    Es1_max; % Es1(6) = Es1_max

    0; % Es2(0) - Es2(T) = 0
    Es2_max; % Es2(6) = Es2-max

    0; % Es3(0) - Es3(T) = 0
    Es3_max; % Es3(6) = Es3-max
```

```
    0; % Es4(0) - Es4(T) = 0
    Es4_max; % Es4(6) = Es4-max

    0; % Es5(0) - Es5(T) = 0
    Es5_max; % Es5(6) = Es5-max

    0; % Es6(0) - Es6(T) = 0
    Es6_max; % Es6(6) = Es6-max

    % lunar VSAT modules disconnected from grid
    % Pg1(T) - Psc1(T) + Psd1(T) = Pd1(t)
    Pd1(n);
    % Pg2(T) - Psc2(T) + Psd2(T) = Pd2(t)
    Pd2(n);
    % Pg3(T) - Psc3(T) + Psd3(T) = Pd3(t)
    Pd3(n);

    % lunar base modules share power
     % -Psc4(T) + Psd4(T) - Psc5(T) + Psd5(T) -
Psc6(T) + Psd6(T) = Pd4(T) + Pd5(T) + Pd6(T)
    (Pd4(n) + Pd5(n) + Pd6(n))
];

lb = [
    zeros(n,1); % Pg1(1..T)
    zeros(n,1); % Psc1(1..T)
    zeros(n,1); % Psd1(1..T)

    zeros(n,1); % Pg2(1..T)
    zeros(n,1); % Psc2(1..T)
    zeros(n,1); % Psd2(1..T)

    zeros(n,1); % Pg3(1..T)
    zeros(n,1); % Psc3(1..T)
    zeros(n,1); % Psd3(1..T)

    zeros(n,1); % Psc4(1..T)
    zeros(n,1); % Psd4(1..T)

    zeros(n,1); % Psc5(1..T)
    zeros(n,1); % Psd5(1..T)

    zeros(n,1); % Psc6(1..T)
    zeros(n,1); % Psd6(1..T)

    zeros(n+1,1); % Es1(0..T)
    zeros(n+1,1); % Es2(0..T)
    zeros(n+1,1); % Es3(0..T)
    zeros(n+1,1); % Es4(0..6)
    zeros(n+1,1); % Es5(0..6)
    zeros(n+1,1); % Es6(0..6)
];
ub = [
    Pg1_max * ones(n-1,1); % Pg1(1..6)
    0; % Pg1(T)
    Psc1_max * ones(n,1); % Psc1(1..T)
    Psd1_max * ones(n,1); % Psd1(1..T)

    Pg2_max * ones(n-1,1); % Pg2(1..6)
    0; % Pg2(T)
    Psc2_max * ones(n,1); % Psc2(1..T)
    Psd2_max * ones(n,1); % Psd2(1..T)

    Pg3_max * ones(n-1,1); % Pg3(1..6)
    0; % Pg3(T)
    Psc3_max * ones(n,1); % Psc3(1..T)
    Psd3_max * ones(n,1); % Psd3(1..T)

    Psc4_max * ones(n,1); % Psc4(1..T)
    Psd4_max * ones(n,1); % Psd4(1..T)

    Psc5_max * ones(n,1); % Psc5(1..T)
    Psd5_max * ones(n,1); % Psd5(1..T)

    Psc6_max * ones(n,1); % Psc6(1..T)
    Psd6_max * ones(n,1); % Psd6(1..T)

    Es1_max * ones(n+1,1); % Es1(0..T)
    Es2_max * ones(n+1,1); % Es2(0..T)
    Es3_max * ones(n+1,1); % Es3(0..T)
    Es4_max * ones(n+1,1); % Es4(0..T)
    Es5_max * ones(n+1,1); % Es5(0..T)
    Es6_max * ones(n+1,1); % Es6(0..T)
  ];

x = linprog(f, [], [], Aeq, beq, lb, ub);

Pg1 = x(1:n);
Psc1 = x(n+1:2*n);
Psd1 = x(2*n+1:3*n);

Pg2 = x(3*n+1:4*n);
Psc2 = x(4*n+1:5*n);
Psd2 = x(5*n+1:6*n);

Pg3 = x(6*n+1:7*n);
Psc3 = x(7*n+1:8*n);
Psd3 = x(8*n+1:9*n);

Psc4 = x(9*n+1:10*n);
Psd4 = x(10*n+1:11*n);

Psc5 = x(11*n+1:12*n);
Psd5 = x(12*n+1:13*n);

Psc6 = x(13*n+1:14*n);
Psd6 = x(14*n+1:15*n);

Es1 = x(15*n+1:16*n+1);
Es2 = x(16*n+2:17*n+2);
Es3 = x(17*n+3:18*n+3);
Es4 = x(18*n+4:19*n+4);
Es5 = x(19*n+5:20*n+5);
Es6 = x(20*n+6:21*n+6);
```

VIII. REFERENCES

[1] A. J. Colozza and Vantage Partners, LLC. (2020, March). Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison. [Online]. https://core.ac.uk/download/pdf/288485222.pdf

[2] G. A. Landis, S. G. Bailey, D. J, Brinker, D, J, Flood. (1990, January). Photovoltaic Power for a Lunar Base. [Online]. https://www.sciencedirect.com/science/article/pii/009457659090021C

[3] G. E. V. Awdry. (1954). Development Of A Lunar Base. *Journal of the British Interplanetary Society. 13*, pp. 166-169.

[4] G. Hu, S. Zhao, Z. Sun, and C. Yao. (2013, July). A Heat Pipe Cooled Modular Reactor Concept for Manned Lunar Base Application. [Online]. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1078.7885&rep=rep1&type=pdf

[5] L. S. Mason, H. S. Bloomfield, and D. C. Hainley. (1989, January). SP-100 Power System Conceptual Design for Lunar Base Applications. [Online]. https://pdfs.semanticscholar.org/4e9e/d54cbdb95a9448f46ab4022c301ac162a566.pdf

[6] National Aeronautics and Space Administration Space Technology Mission Directorate. (2020, September). Lunar Vertical Solar Array Technology Appendix 80HQTR20NOA01-20GCD_C1. [Online]. https://nspires.nasaprs.com/external/viewrepositorydocument?cmdocumentid=778013&solicitationId={68A7EFE3-1B4F-5AA1-A169-119D97C8DB8F}&viewSolicitationDocument=1

[7] National Aeronautics and Space Administration Space Technology Mission Directorate. (2020, October). Space Technology Research, Development, Demonstration, and Infusion-2020 (SpacTech-REDDI-2020). [Online]. https://nspires.nasaprs.com/external/viewrepositorydocument?cmdocumentid=710467&solicitationId={68A7EFE3-1B4F-5AA1-A169-119D97C8DB8F}&viewSolicitationDocument=1

[8] P. L. Sowerby. (1954). Structural Problems of the Lunar Base. *Journal of the British Interplanetary Society. 13*, pp 36-40.

[9] Suntria. (2020). Tesla Powerwall. [Online]. https://suntria.com/tesla-powerwall/

[10] Triton Solar. (2020). 10 kWH Battery. [Online]. https://www.tritonsolar.com/10kwh-battery/